Prediction of Streamflow to Assess Trade-offs from Water Policy Rules and Land Use Intensification

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Abstract: This paper presents results obtained from an approach utilised to predict streamflow in ungauged catchments. Yass catchment, a dryland catchment in the Upper Murrumbidgee was the study area used. A conceptual rainfall-runoff model, IHACRES, was adopted in conjunction with a GIS containing soil and vegetation information and a rainfall estimation procedure, to relate streamflow to catchment characteristics. The ANUSPLIN package was applied to create long term mean monthly and annual rainfall surfaces from thin plate smoothing splines for the entire catchment. A scaling procedure was then used to generate daily rainfall estimates which were utilised as input for the conceptual rainfall-runoff model. Catchment-scale daily streamflow estimates were predicted for twelve subcatchments ranging in size from 23km^2 to 290km^2. The approach could be of use in identifying appropriate water allocation rules in unregulated river systems, particularly where knowledge of biophysical data and human induced extractions is sparse. The results are to be utilised in an integrated modelling tool to predict impacts for land and water systems as a result of policy imposition such as those associated with the NSW COAG Water Reforms.

Keywords: Ungauged catchment; Streamflow prediction; Catchment-scale; Integrated modelling

1. INTRODUCTION

1.1 Water Policy Setting

Water policy issues introduced by the NSW Government are designed to balance environmental and socio-economic needs at the catchment scale. The potential for a set of environmental policies to negate existing environmental efforts is one reason why interpolicy impacts are required to be identified. In addition, a set of physical impacts upon the catchment can be expected with any policy option implemented. Each option has a set of onsite and offsite consequences. Adverse or negative impacts of these kind are considered to be trade-offs. Trade-offs are socio-economic or biophysical. The optimal policy option requires an understanding of trade-offs between land and water systems as well as potential impacts upon other policy options to identify what options are most suitable for whole catchment systems.

1.2 The Modelling Approach

An integrated modelling approach is designed and applied at the catchment scale in order to:

- Qualitatively and quantitatively identify inter-policy impacts
- Quantitatively identify environmental impacts and trade-offs in time and space as a result of introducing several land and water policy options

A conceptual framework underpinning the approach would identify all relevant aspects of integration between economic, environmental and hydrological systems [see, for example, Gilmour and Watson 2001]. This paper presents part of the approach used to model the hydrological system.

1.3 Study Catchment

The Yass catchment is an unregulated river system located in the Upper Murrumbidgee. The catchment suffers from water quantity problems as a result of the overextraction of water resources, and water quality problems as indicated by the presence of highly salinised land and water systems. The tributaries used for estimating streamflow are indicated by Figure 1.

The purpose of the study was to develop an approach for predicting streamflow within ungauged systems by utilising a hydrological model which could be obtained by relating its parameters to landscape activities. Critical considerations in selecting an appropriate hydrological model were as follows:

- Allow for the application at a range of spatial scales
- Minimise the number of parameters to allow ease of transfer between catchments
- Allow parameter values in the hydrological model to be related to catchment attributes within ungauged modelling areas
- Sufficient complexity to ensure the uniqueness of Australian catchments is considered ie. the effect of antecedent soil conditions and partitioning between recharge and runoff
- Permit annual, monthly and daily estimation for the purpose of obtaining crude streamflow estimates for use in answering a series of water policy questions over short and long run time spans.

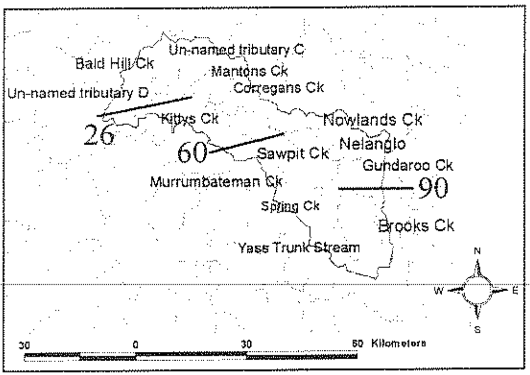

Figure 1. Yass Catchment Tributaries.

It would appear that a conceptually based model would best fit the above criteria for the modelling application. The IHACRES model has been successfully applied at various scales. Its widely successful application is partly due to the relatively small number of parameters required for calibration. Despite this, the structure of the model is sufficiently complex in representing essential catchment processes such as subsurface flow and evapotranspiration as well as baseflow separation. The IHACRES model has been successfully applied across a wide range of climatic environments, although Jakeman et al. [1993] suggest that it should not be utilised where annual precipitation is less than 300mm per annum. It has been utilised in catchment-scale land use change analysis and as a tool in answering hydrologically focused water management questions. In addition, the model has also been utilised in regionalisation studies [e.g. Post and Jakeman, 1996]. For a description of the model structure and its areas of application see Jakeman et al. [1990], Jakeman et al. [1993], Jakeman and Hornberger, [1993], Ye et al. [1997] and Schreider et al. [1996].

2. METHODS

Three streamflow gauges are located in Yass catchment and are indicated by Figure 1.Gauge 90h and 60 drain an area of 388 km^2 and 26 km^2. respectively. This gauge is downstream of Yass weir; responsible for extracting the township water supply.

2.1 Selecting Parameters for Unit Hydrograph Development

A power law function was utilised to define recession characteristics and timing of events pertaining to the unit hydrograph [Croke, 2001]. The two-parameter function used to fit the observed hydrograph was:

$$y=1/[1+[x/a]^{b}]$$

In order to derive the observed unit hydrograph, events were selected from the stream discharge history. A detailed description of the procedure can be found in Croke [2001]. The hydrograph peaks selected were used to identify a mean unit hydrograph for the gauged catchments. The parameter values for the power law function were then derived from the mean unit hydrograph response curve. For computational efficiency, the power law was then converted into a series of exponential terms. The results are indicated in Table 1. Parameter 'a' is the time taken for the flow to fall to half the peak flow, and therefore gives a measure of the width of the recession curve.

Table 1. Estimation of unit hydrograph using the fitting technique.

Number of peaks identified	Parameter a	Exponential Terms
Gauge 90 using daily data		
73	0.45	6
29	0.31	6
Gauge 60 using daily data		
116	0.24	6
120	0.54	6
Gauge 26 using hourly data		
14	0.14	5
11	0.41	4

As Table 1 indicates, an estimation of model parameters was most stable for Gauge 90 and less so for Gauge 60. Based upon these results, it was decided to exclude Gauge 26 [downstream of Yass weir] and Gauge 60 [short period of record] from the analysis in obtaining appropriate model parameters for use in predicting streamflow upon the surrounding ungauged subcatchments. The second parameter b was essentially constant, and so is not shown in Table 1.

The derived unit hydrograph and fitted power law are shown in Figure 2 (where a = 0.45 and b = 2.00). This fit yielded a 6 exponential term model which was used within the rainfall-runoff model. The derived unit hydrograph is likely to be affected by subsequent flow peaks, resulting in deviations from the true unit hydrograph, particularly at longer times from the peak.

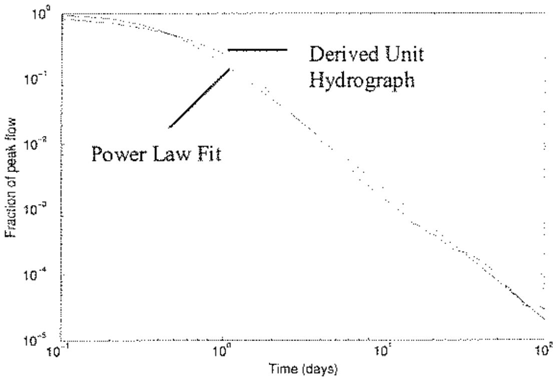

Figure 2. A two parameter power law fit to Gauge 90 streamflow data.

2.2 Rainfall Estimation Using Thin Plate Smoothing Splines

Smoothing splines were used to generate monthly rainfall surfaces for the catchment from time series rainfall data at individual gauges. The model identifies an estimate of noise within the data and applies a smoothing function estimate *z*. There are *n* data values specified by a position in Euclidean space defined by $y[x_i]$ and $z[x_i]$ where $z[x_i]$ is a function to be estimated from the observations and $\varepsilon[x_i]$ is a discontinuous error term across the Euclidean space [Hutchinson, 1995]. The term $z[x_i]$ is an unknown smoothing function that is to be estimated while x_i defines co-ordinate positions of the spatial observations $y[x_i]$ given by

$$y[x_i]=z[x_i] + \varepsilon[x_i] \quad [i=1,\dots,n]$$

A full definition of the model can be found in Hutchinson [1995]. The model assumes that rainfall is spatially correlated with latitude, longitude and elevation. An advantage of using thin plate smoothing splines over other interpolation techniques is that the spatial auto-covariance structure does not need to be defined prior to model use. Standard fitting techniques often require significant time and resources to estimate the structure, given that variance of data errors change across the rain gauge network. Secondly, interpolation techniques are often limited in application by the difficulty in obtaining an appropriate smoothing parameter. The smoothing parameter is optimised by minimising the generalised cross validation [GCV], implicit within the model structure. The GCV is an estimate of predictive error of the spline surface. It is calculated by removing each data point and summing the square of the difference of each point from a surface fitted by all other data points [Hutchinson and Gessler, 1994].

The ANUSPLIN software package was utilised to develop a set of twelve long-term mean monthly rainfall surfaces. For each station, independent model variables needed to be calculated. The number of years of the record, latitude, longitude, elevation and relative rainfall error were calculated for this purpose. Geo-referencing data was obtained by interrogation of a DEM using the GIS package ARC/INFO for all 680 data points. The information was placed in a text file to be used as an input file for the model. Other information to be determined prior to model use were the transformation parameters, order of the spline, smoothing directive and optimisation directive [see Hutchinson 1995 for a full explanation of each]. The SPLINA model was utilised to construct long term mean monthly rainfall estimated for each of the twelve months. The program LAPGRD was utilised to calculate a regular two-dimensional grid of interpolated points covering the entire Upper Murrumbidgee catchment. LAPGRD required a digital elevation model, imported for use by the program, to construct the grid. This allowed a standard rainfall mean to be determined at any point within the DEM when developed with the SPLINA coefficients.

2.3 Rainfall Partitioning Using Catchment Attributes

For each of the twelve subcatchments in Yass catchment, an average annual rainfall estimate was obtained from the rainfall surface results based on subcatchment area. A GIS layer of broad soil types was obtained from the NSW Department of Agriculture and a detailed vegetation layer was obtained from the Department of Land and Water Conservation.

Each land use and soil proportion was summed across each subcatchment to give a composite fraction of landuse and soil type. The land use and soil type were then used to calculate an annual estimate of potential evapotranspiration, after which partitioning between recharge and runoff was carried out based on soil type.

2.4 IHACRES Model Development on Gauged Catchments

A modified version of the IHACRES rainfall-runoff model was developed to predict flow at the two gauges [Croke and Jakeman, 2001]. The modified model involves fitting the power law function or exponential function to selected peak hydrograph events. The results in Table 2 show that for the upper catchment the efficiency of the model fit was 0.81. The objective functions O_1 and O_2 are given by:

$$O_1 = \Sigma\, [sqrt[Q_o] - sqrt[Q_m]]$$

$$O_2 = \Sigma\, [1/[1+Q_o] - 1/[1+Q_m]]$$

where Q_o is the observed flow, and Q_m is the modelled flow. The first objective function indicates model fit to peak flows while the second indicates the fit for low flows.

Table 2. Calibration results for Yass catchment gauge using the modified IHACRES model.

Gauge	Model efficiency [R^2]	O_1	O_2
90 Upper catchment	0.81	133	19
26 Lower catchment	0.65	127	28

The Yass lower catchment gauge is downstream of Yass weir. Extractions from this section of the river remove base flow throughout most of the year.

Model efficiency for the lower catchment was 0.65 while the objective function values were of a similar order to those of the upper catchment. Data as to the volume of extractions was obtained in an attempt to restore natural flows to improve the model calibration. However, this did not improve model efficiency, as information pertaining to distribution of extractions was not available on a daily basis.

2.5 The Modified Rainfall-Runoff Model for Ungauged Catchments

A modified version of the IHACRES model was developed to incorporate the evapotranspiration versus rainfall relationships developed by Zhang et al. [2001] to estimate streamflow on ungauged catchments. For a full description of the model, see Croke and Jakeman [2001]. The approach relies upon identifying evapotranspiration from mean annual rainfall and adjusting the IHACRES model parameters to obtain the closest estimate of the evapotranspiration. The IHACRES model then generates streamflow, using the adjusted parameter values.

The IHACRES model inputs were temperature, rainfall, evapotranspiration and a recharge coefficient. Actual evapotranspiration was calculated using

$$ET = fE_f + [1-f]E_g$$

where ET is the estimated evapotranspiration estimated, f is the fraction of forest or grass cover, E_f is the estimated evapotranspiration from a forested catchment and E_g is the estimated evapotranspiration from a grassed catchment [Zhang et al. 2001]. The effective forest fraction was calculated using

$$f = \sum_{lu} f_{lu} \frac{A_{lu}}{A}$$

where f_{lu} is the effective forest fraction attributable to a particular land use [Dawes et al. 2001], A_{lu} is the area with the land use, and A is the total subcatchment area. The calculations were carried out on all twelve subcatchments.

Determination of actual evapotranspiration on each subcatchment allowed an effective rainfall to be identified. Effective rainfall, according to soil type, was partitioned between runoff and recharge:

$$Q_{recharge} = [P - ET_{actual}][Soil_f]$$

where P is an annual rainfall estimate, ET_{actual} is estimated evapotranspiration, $Soil_f$ is the estimated fraction of excess rainfall that becomes recharge [based upon Petherum curves] and Q is volume of flow [see Zhang et al. 2001 for a description of Petherum curves].

The estimated parameters were used as input into the IHACRES model. The model was run in simulation mode given that the parameters, land cover and area were fixed. In addition, a two-day delay was added to the model to allow for the delay between rainfall and catchment response as streamflow. Where a streamflow and rainfall record is normally required for calibration or simulation, the twenty-year daily rainfall record for each subcatchment was used as input into the simulation. Streamflow was generated using the relationships defined by Zhang et al. [2001] to partition rainfall into recharge and runoff components in addition to utilising the model conceptual framework to produce a unit hydrograph for each subcatchment. The shape of the unit hydrograph was estimated using the two-parameter power law fit to the gauged unit hydrograph.

3. RESULTS

3.1 Rainfall Estimation Results

Initially, 91 rainfall stations were used to construct the rainfall surfaces for Yass catchment. Although yielding statistically sound results, it was found that the twelve surfaces contained lower than expected rainfall in the lower catchment of Yass, effectively presenting a hole in the rainfall surface. For this reason, a second pass was conducted utilising gauges from the entire upper Murrumbidgee catchment, using 680 stations after data editing. The Murrumbidgee surface estimates corrected the initial data errors that occurred in utilising a rain gauge density over a smaller spatial error. A larger rain gauge network has the potential to reduce errors through the smoothing process where the larger network contains less data errors. Table 3 illustrates the long-term annual rainfall obtained from the initial spline estimates and the corrected estimates as a result of adjusting the rain gauge density from the Yass catchment to the entire Upper Murrumbidgee.

Table 3. A comparison of long term annual rainfall estimation in mm.

Yass Sub-Catchments	Yass catchment surface estimate	Upper Murrumbidgee surface estimate
Kittys	528	743
Nowlands	572	745
Murrumbateman	374	729
Obriens	377	803
Mantons	566	753
Bald Hill	566	766
Brooks	622	714
Spring	618	691
Gundaroo	666	724
Nelanglo	395	714
Corregans	564	744
Five Mile	645	715

Table 4 illustrates statistical results obtained from the rainfall surface construction. The results illustrate a signal of about half the number of data points utilised for surface construction; considered desirable as identified in the model structure. The mean annual rainfall estimates contain a small standard deviation, the magnitude of which is expected within long term seasonal limits. The generalised cross validation [GCV] is particularly low for the months of September, October and November, suggesting a good model fit between surface values and actual rainfall values.

Table 4. Results from the ANUSPLIN Program.

Month	Mean [mm]	St.Dev	Signal %	Square root of the GCV mm
Jan	59.2	14.1	53.6	1.09
Feb	54.7	14.4	85.6	1.25
Mar	59.0	14.8	56	1.11
Apr	51.7	12.8	53	1.24
May	50.3	14.2	15.3	0.95
Jun	57.0	11.0	22.5	1.04
Jul	59.0	11.1	43.2	1.10
Aug	51.7	10.6	18.6	1.10
Sep	56.2	9.80	25.6	0.975
Oct	54.3	14.3	25.8	0.972
Nov	51.3	14.5	46.5	0.961
Dec	49.3	14.3	62.0	0.961

3.2 Streamflow Estimation Results

Figure 3 illustrates the result obtained from testing the approach on the gauged catchment 90. The approach predicts the streamflow well, with a small negative bias as indicated by the error. The approach slightly overestimates streamflow for large rainfall events as Figure 3 illustrates. This is expected given the ephemeral nature of the tributaries and loss to groundwater. The evapotranspiration estimate given by the Zhang relationships and the IHACRES model obtained were 557mm and 569mm respectively.

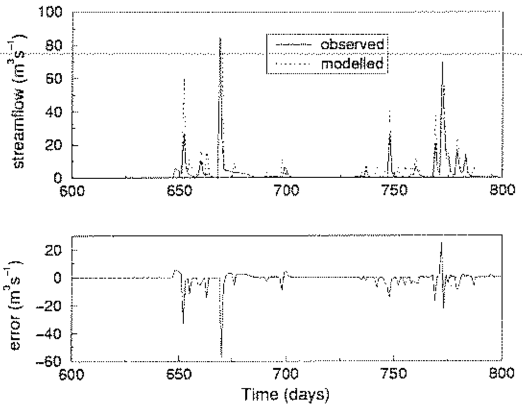

Figure 3. A comparison of daily observed and predicted streamflow.

The model estimate is sufficient to identify streamflow at the catchment scale, and as such, illustrates the usefulness of the approach in estimating streamflow for answering catchment scale land and water policy questions. The regionalisation approach will be tested in gauged catchment in the Upper Murrumbidgee, including those found in Croke et al 2001.

4. CONCLUSIONS

The paper has presented a procedure for estimating streamflow for ungauged catchments, and in particular, unregulated river systems. The results are to be utilised in an integrated modelling environment designed to analyse the impacts of policy questions upon land and water systems. The foundation of the integrated model is the hydrological network, of which part of its design and derivation has been presented.

The method requires good quality gauged data to derive the appropriate parameters for use in streamflow estimation. Gauged data should be obtained from areas of similar land use and catchment attributes but not necessarily from the same geographic location. Thin plate smoothing splines combined with a scaling procedure for rainfall estimation provide an estimation of spatially varying rainfall. However, the results show that a minimum grid scale is required to identify daily rainfall for the purpose of streamflow modelling. This is illustrated by the greater accuracy in results when moving from the Yass catchment to the Upper Murrumbidgee regional scale. Streamflow estimation using this approach should provide an estimate that is reasonable for assessing catchment scale water allocation issues. Future work will involve testing the proceedure on catchments within the Upper Murrumbidgee where a large number of discharge sites is available.

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